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Converting a C-130 Hercules into a Compound Helicopter: A Conceptual Design Study

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Background

Currently, the US Military and NASA are investigating the feasibility of a Vertical/Short Take Off and Landing (VSTOL) aircraft that can provide invaluable aid in the combat theater and significantly improve the civil transportation system. The nominal military mission requirement calls for a 28-ton payload heavy lift capability while the civilian requirements calls for a 90-passenger, 1000-nm range, airliner, as noted in Reference 1. To aid in these aircraft requirements, the present study examined the conversion of a Lockheed Martin C-130 Hercules into a compound aircraft, which would demonstrate the technology required by a much larger version.

Study Approach

To create a cost effective technology demonstrator, this study selected the C-130H, shown in Figure 1, as a baseline aircraft to which a VTOL capability would be added. An important guideline that was kept in mind throughout the entire study was to make as few changes to the C-130H as possible.

The C-130H's maximum takeoff gross weight of 155,000 pounds was retained. Any changes and additions to the propulsion/lifting systems would reduce the C-130H's useful load of 49,000 pounds. Major aircraft components such as the fuselage, cargo handling, vertical and horizontal control surfaces, and landing gear would be unchanged.

Figure 1. Lockheed Martin C-130H http://www.military-aircraft.org.uk

Two configurations of VTOL capability were studied. The first configuration envisioned was a single main rotor – fuselage mounted – along with a pair of turboshaft engines. In this approach, the current C-130H wing, engines and four propellers (used for anti-torque in hover and low speed) were retained to the maximum extent possible. The second configuration was patterned after the Russian Kamov Ka-22, which is shown in Figure 2. Both VTOL C-130H configurations required rotor blade conceptual design using the advanced carbon filament M55J to minimize the useful load penalty.

Figure 2. Kamov Ka-22 http://www.wikipedia.org

C-130H Baseline Design. The C-130H started production in 1965 and has been used extensively within the US military as a tactical airlift aircraft. Capable of taking off with over 49,000 lb of payload in 4,000 ft, the C-130 presented a proven baseline design to make V/STOL modifications to. Baseline properties and specifications are shown in Table 1 as taken from Reference 5.

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Table 1. C-130H specifications

C-130H Specifications – Jane's All the World's Aircraft 1995-1996	
Wing span	132 ft 7 in
Wing chord (mean)	13 ft 8.5 in
Length	97 ft 9 in
Operating Weight Empty	76,469 lb
Max Internal Fuel Weight	44,330 lb
Max Payload	49,818 lb
Max Normal Take Off Weight	155,000 lb
Power plant	4 x Allison T56-A-15 (4,508 ehp)
Take Off Run	4,000 ft

Rotor Blade Design. The blade conceptual design process consisted of creating an Excel spreadsheet that used first order analysis to determine if a given design point would meet constraints. This investigation consisted of aerodynamic and structural blade element analysis. Such investigation provided values for important characteristics such as loaded tip deflection, power required to hover, and blade weight. The aerodynamic blade element analysis was implemented using the hover equations presented in Reference 2. The structural analysis involved two portions. First was the calculation of a blade cross sectional Structural Stiffness (EI_{xx}); second was the calculation of the total blade deflection using basic beam bending equations. All structural equations used were taken from Reference 3.

To minimize the reduction in the C-130H's aircraft lift to drag ratio, a low drag rotor hub similar to that of the Lockheed AH-56 Cheyenne attack helicopter, Figure 3, was selected.

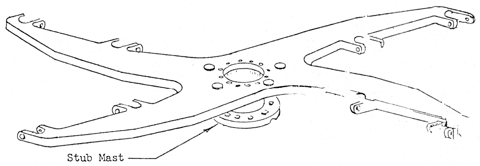

Figure 3. Lockheed AH-56 low drag hub design

Once the first pass on the design point had been conducted, the second layer of analysis involved using the NASA Design and Analysis of Rotorcraft code (NDARC), listed in Reference 4, developed by Wayne Johnson at NASA Ames Research Center, Moffett Field, CA. NDARC is able to provide weights and performance data for a given rotorcraft design under a variety of mission specifications.

Design Constraints. The following five constraints were used to determine the effectiveness of a given blade design: thrust produced (including gross weight and download), tip deflection, maximum tensile stress, maximum compressive stress, and blade flap (M=2) mode frequency. The constraints and their respective values are listed in Table 2 below.

Table 2. Constraints against which design points were checked.

Constraint	Constraint Value	Justification
Thrust	178,250 lb total	Mission Specification
Tip Deflection	0.15 x R	Historical Data
Maximum Tensile Stress	270,000 psi	Material Limit
Maximum Compressive Stress	120,000 psi	Material Limit
Blade Flap Mode (M=2)	$\omega_{M=2}/\Omega < 2.5$ or $\omega_{M=2}/\Omega > 3.5$	Historical Data

Aerodynamic Analysis.

At each location along the blade span, the induced velocity was calculated based on the pitch angle and chord at that radial station. From this, the effective section angle of attack was determined, which was then used to calculate the section C_T. This was integrated along the blade span for total lift and torque.

A preliminary power trade study, using the above aerodynamic torque analysis, produced the following graph, Figure 4. The clear dependence of power on rotor radius was a driving factor throughout the study, as efforts were made to maximize the rotor radius, thus requiring less power.

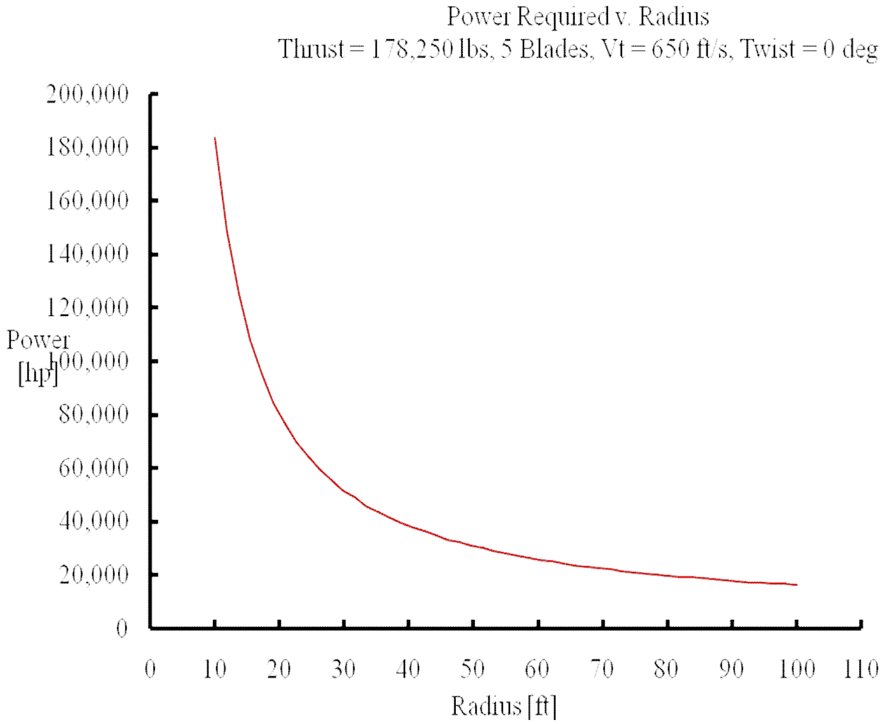

Figure 4. Preliminary study of power required v. rotor radius

Structural Analysis.

The blade section was modeled as a two-part airfoil. The leading edge was modeled as a semi ellipse with a straight tapering to a point of the trailing edge.

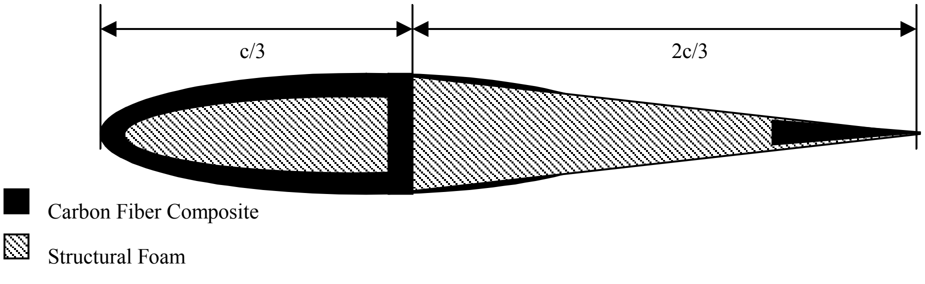

Figure 5. Cross-sectional composition of blade airfoil

The blade cross sectional Area Moment of Inertia (I_{xx}) was calculated in multiple steps, each step corresponding to a different area of the blade cross section. The EI_{xx} of each area was calculated independently where the blade cross sectional EI_{xx} is the sum of all the independent EI_{xx}'s.

The moments due to lift, blade weight, and centrifugal force were calculated for the entire blade span. This was then used in the basic beam bending equation along with the EI_{xx} to determine the total tip deflection.

Results

Single Main Rotor Design. Using the above methodology, various designs and configurations were examined. For the single main rotor set of design points, the number of blades was set at five. The original goal of developing a blade for a single main rotor, C-130 compound was found to exceed the tip deflection limit as well as the material stress and blade flap mode frequency limits as shown in Table 3 below.

Table 3. Tabulated values for the initial design point.

Initial Design (Input) 4,000 ft and 95 deg F		
Number of Rotors	1	
Number of Blades	5	
Radius	90 ft	
C_T/Solidity	0.19	
Blade Root Angle	17.84 deg	
Tip Speed	650 ft/sec	
Constraint Values		
Thrust	178,250 lb	Constraint Met
Tip Deflection	129 ft	Constraint NOT Met
Maximum Tensile Stress	535,357 psi	Constraint NOT Met
Maximum Compressive Stress	530,981 psi	Constraint NOT Met
Blade Flap Mode (M=2): $\omega_{M=2}/\Omega$	3.08	Constraint NOT Met
Rotor Characteristics (Output)		
Power Required	17,732 hp x 1 Rotor	
Blade Weight	1,398 lb x (5 Blades/Rotor)	

Further analysis on a single main rotor design resulted in the following trade study, Figure 6.

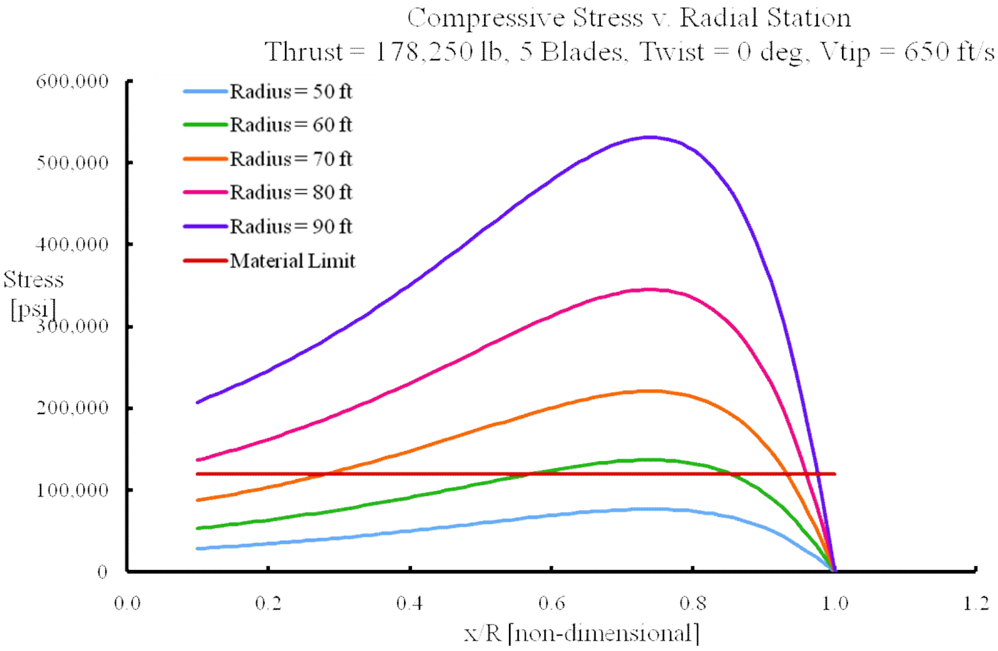

Figure 6. Trade study of compressive stress v. radial station

Thus, for a single main rotor that met the compressive stress constraint, the most stringent limit, a rotor radius of approximately 55 ft was necessary. This corresponded to a required power of nearly 28,000 hp and a blade weight of around 1,650 lb.

Twin Rotor Design. At this point, the decision was made to switch to a twin rotor compound configuration, much in the same style as the Kamov Ka-22. Some benefits associated with such a configuration were reduced power requirements due to two main rotors and lack of anti torque mechanisms because of the contra-rotating rotors. However, having two rotors, one on each wing tip would also require a cross-shaft running though the span of the entire wing for One-Engine Inoperative contingency cases.

Following this line of reasoning, various trade studies using the same methodology as the Single Main Rotor Design were run in order to determine the most effective blade design. The resulting design point is listed in Table 4, and was also used in NDARC. Full results from NDARC will be provided in the full paper.

Table 4. Tabulated values for chosen design point for NDARC input.

Chosen Design (Input) 4,000 ft and 95 deg F		
Number of Rotors	2	
Number of Blades	3	
Radius	62.9 ft	
C_T/Solidity	0.15	
Blade Root Angle	16.06 deg	
Tip Speed	650 ft/sec	
Constraint Values		
Thrust	89,125 lb x 2 Rotors	Constraint Met
Tip Deflection	9.44 ft	Constraint Met
Maximum Tensile Stress	121,279 psi	Constraint Met
Maximum Compressive Stress	116,348 psi	Constraint Met
Blade Flap Mode (M=2): $\omega_{M=2}/\Omega$	4.53	Constraint Met
Rotor Characteristics (Output)		
Power Required	9,016 hp x 2 Rotors	
Blade Weight	1,684 lb x 3 (Blades/Rotor) x2 Rotors	

Status

The present study examined various configurations and rotor blade designs in order to fulfill the nominal mission described previously. It was shown that the initial design of a 180 ft diameter rotor to lift 155,000 lb was not feasible due to material constraints. A revised design, in which the rotor radius was reduced to 55 ft, met the given constraints but required too much power.

The decision was made to move to a twin rotor compound to take advantage of the increased disc area and drop the need for anti torque devices. Following this design shift, a new design point was found where all five constraints were met and the power requirements were deemed reasonable. This twin-rotor design was used in NDARC to provide a complete sizing analysis of the chosen design point.

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